ADVANCEMENTS IN BIDIRECTIONAL DC/DC CONVERTERS WITH DUAL-BATTERY ENERGY STORAGE FOR HYBRID ELECTRIC VEHICLES: A COMPREHENSIVE REVIEW

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Abstract: *This review paper provides a comprehensive examination of the recent developments in bidirectional DC/DC converters featuring dual-battery energy storage systems for hybrid electric vehicles (HEVs). As the automotive industry embraces electrification, the integration of dual-battery setups and bidirectional converters plays a pivotal role in optimizing energy management and enhancing overall vehicle performance. The paper synthesizes and analyzes key research findings, technical innovations, and challenges associated with these emerging technologies. Insights from this review contribute to the understanding of state-of-the-art solutions and inform future developments in the field of hybrid electric vehicle energy storage and power electronics. Furthermore, the review highlights emerging trends, research gaps, and potential avenues for future exploration in the realm of bidirectional DC/DC converters and dual-battery energy storage for HEVs. Insights derived from this comprehensive analysis provide valuable guidance for researchers, engineers, and industry stakeholders, fostering continued progress in the field of electrified transportation. Ultimately, this review aims to contribute to the evolution of sustainable and efficient energy management solutions for the next generation of hybrid electric vehicles.*

Keywords: *Bidirectional DC/DC Converters, Dual-Battery Energy Storage, Hybrid Electric Vehicles (HEVs), Energy Management, Electrified Transportation.*

1. INTRODUCTION

The consumption of fossil fuels such as oil and natural gas, and the increase of greenhouse gas emissions are having a serious impact on the climate and environment. With the increasing shortage of non-renewable energy, energy security has gradually been paid attention by governments. In recent years, vehicle ownership in various countries has increased year by year, and new energy vehicles (NEV) with unconventional vehicle fuels as power sources help to reduce the dependence of transport on non-renewable energy and reduce pollution emissions, and their ratio in vehicles is increasing year by year. According to the consultative draft of New Energy Automobile Industry Development Plan (2021–2035), China's market share of NEV will be 20% by 2025 [1]. Hydrogen fuel cell vehicle (FCV) holdings are expected to reach 100,000 in 2025 and 1 million in 2035, according to Technology Roadmap for Energy Saving and New Energy Vehicles 2.0 [2]. Plug-in hybrid electric vehicle (PHEV) holdings are expected to peak in 2025 [3]. In addition, Bloomberg NEF predicts that by the end of 2022, more than 26 million NEV will be on the road around the world [4].

In the ever-evolving landscape of electrified transportation, the development of efficient energy storage and management systems is pivotal for the continued advancement of hybrid electric vehicles (HEVs). One critical component influencing the performance and energy dynamics of HEVs is the bidirectional DC/DC converter, particularly when integrated with dual-battery energy storage configurations. This comprehensive review delves into the recent advancements in this domain, aiming to provide a thorough understanding of the technological landscape, challenges, and potential avenues for future research. The advent of hybrid electric vehicles marks a significant stride toward achieving sustainable and energy-efficient transportation. HEVs employ a combination of internal combustion engines and electric propulsion systems, necessitating sophisticated power electronics for seamless energy flow and optimal performance. At the heart of this energy management lies the bidirectional DC/DC converter, a key element responsible for regulating power exchange between the high-voltage and low-voltage electrical systems.

This review explores the technical intricacies of bidirectional DC/DC converters, highlighting advancements in design methodologies, control strategies, and integration with dual-battery energy storage systems. The dual-battery configuration adds a layer of complexity and opportunity, enabling enhanced energy capacity, efficiency, and dynamic response in HEVs. The paper synthesizes findings from recent research, presenting a comprehensive overview of state-of-the-art developments. Emphasis is placed on key performance metrics such as efficiency, power density, and system stability. The critical evaluation of existing technologies provides insights into the current challenges and opportunities, setting the stage for future advancements in the field.

As electrified transportation continues to gain momentum, understanding and advancing bidirectional DC/DC converters with dual-battery energy storage is crucial for optimizing the efficiency and sustainability of HEVs. This review aims to serve as a valuable resource for researchers, engineers, and industry professionals, fostering a deeper appreciation for the complexities and innovations shaping the future of hybrid electric vehicle technology.

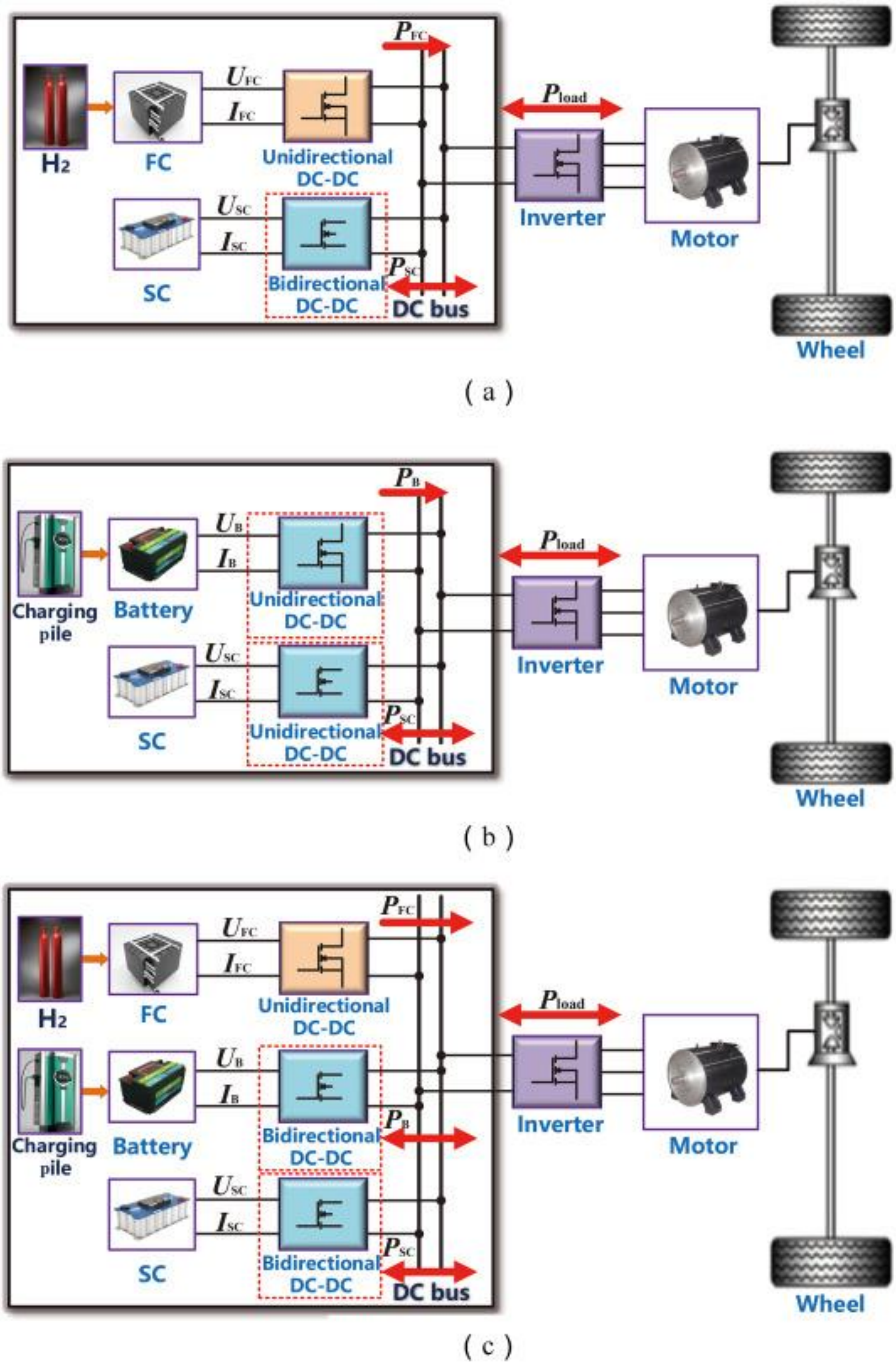

Fig. 1. Structure diagrams of HESS for NEV. (a) HESS for FCV. (b) HESS for PHEV. (c) HESS for FC-PHEV.

II. Basic structure for FCV/HEV

The primary power source is a low-voltage FC stack with SCs connected to FCs in parallel and is depicted in Figure 1 of a standard (FCV/HEV) (Ehsani et al., 2009) power system. The propulsion motor can be powered by the dc-bus voltage that is generated by the driving inverter's dc/dc power components (Haihua and Khambadkone, 2008). Even though the vehicle work to expand design based on ES2, ES1 is utilized as the primary energy storage system medium for peak power generation. It is used to connect the operational inverter's dc bus to dual-energy storage. Several BDCC switches have been distributed to supply particular voltages to loads while controlling power flow between several sources (Tao et al., 2008). Overall cost, mass, and power use are all reduced. The two categories of BDCCs are isolated and non-isolated BDCCs (Bhattacharya et al., 2009).
Electrochemical cells are isolated from one another by using high-frequency transformers in isolated converters All other isolated multiport BDCC topologies, including hop, half or full-bridge circuits, double-active bridges, and other variations, have also been investigated (Krishnaswami and Mohan, 2009). BDCCs that are not isolated have a greater EV success rate than isolated BDCCs (Liu and Chen, 2009). Renewable energy sources, a battery storage system, and a load can all be powered simultaneously via the three-port non-isolated MIMO converter, which utilizes all these converter types. The three double-input converters developed in (Gummi and Ferdowsi, 2010) use a single-pole triple-throw switch and only one inductor. (Zhao et al., 2012). described a modular non-isolated dc MIMO converter. The fundamental boost circuit was improved and integrated into this converter, which is used to hybridize sustainable energy sources in electric vehicles.

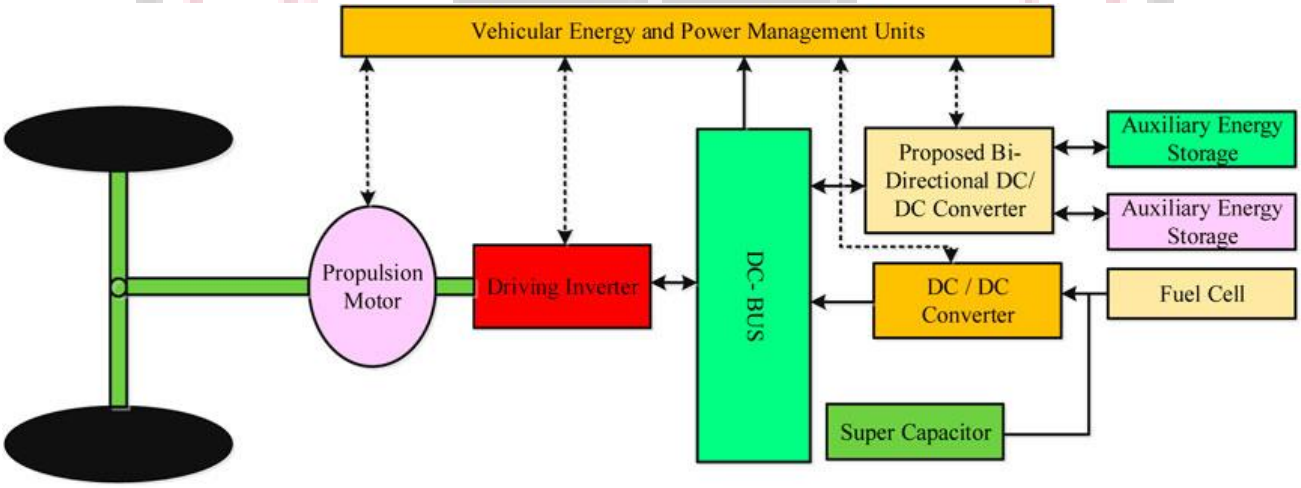

FIGURE 2. Schematic structure for an FCVHEV power system

II. LITERATURE REVIEW

Kharade et al.[1] Presented a significant contribution to electric vehicle (EV) technology by introducing a dual battery charger system. The focus of their research was on advancing the charging system for electric vehicles, addressing critical aspects related to the charging infrastructure. The authors recognized the growing importance of efficient charging solutions in the context of EV adoption and sought to enhance the charging system's performance. By introducing a dual battery charger system, the study aimed to optimize the charging process, potentially reducing charging times and improving overall charging efficiency. The emphasis on charging system advancements reflects a proactive approach to addressing one of the key challenges in the widespread adoption of electric vehicles, making this work valuable for the ongoing development of EV technology and infrastructure.

Chauhan et al. [2] Present a significant contribution to the field of Hybrid Electric Vehicles (HEVs) with their work titled "Multiple PMSG fed Non-inverting buck-boost converter for HEVs." The primary focus of their research is on advancing the design of converters to enhance the performance of HEVs. The proposed converter, a non-inverting buck-boost configuration, is particularly tailored to integrate multiple Permanent Magnet Synchronous Generators (PMSG) into the hybrid vehicle system. This innovative design aims to optimize the energy conversion process, leveraging the unique characteristics of PMSGs. By employing a non-inverting buck-boost topology, the converter is likely engineered to efficiently manage power flow, voltage regulation, and energy harvesting from the PMSGs, contributing to the overall efficiency and performance of Hybrid Electric Vehicles. The study provides valuable insights into the development of

advanced power electronics solutions tailored for the specific requirements of HEVs, emphasizing the importance of multiple PMSGs in achieving enhanced energy conversion and overall system efficiency.
Chen et al. [3] Contribute significantly to the field of renewable energy systems with their work titled "A high step-up three-port dc–dc converter for stand-alone PV/battery power systems." The primary focus of their research is to address the challenges associated with stand-alone photovoltaic (PV) and battery power systems by introducing a high step-up three-port DC-DC converter. The innovative converter design aims to efficiently integrate and manage power from both PV sources and batteries, addressing issues related to voltage matching and energy conversion. The three-port configuration suggests the simultaneous utilization of PV input, battery storage, and load output, emphasizing a versatile and integrated approach to power management in standalone systems. The study provides valuable insights into the development of advanced DC-DC converters tailored for standalone PV/battery power systems, contributing to the optimization of energy harvesting, storage, and distribution in off-grid applications.

Farhangi and Toliyat [4] Make a notable contribution to the field of electric vehicles with their work titled "Modeling and analyzing multiport isolation transformer capacitive components for onboard vehicular power conditioners." The primary focus of their research is on the exploration of multiport isolation transformers and the capacitive components associated with power conditioners in electric vehicles (EVs). The study likely delves into the modeling and analysis of these components, aiming to enhance the understanding of their behavior and impact on the overall performance of power conditioning systems in vehicular applications. By addressing the challenges and intricacies related to multiport isolation transformers and capacitive elements, the research contributes valuable insights into the design and optimization of power conditioning systems, ultimately improving the efficiency and reliability of electric vehicles. This work is pivotal in advancing the knowledge and technology surrounding power electronics for onboard vehicular applications.

Fong et al. [5] Contribute significantly to the field of energy storage with their work titled "Study and development of Mixed Repurposing EV battery system for Stationary energy storage applications." The primary focus of their research is on investigating and developing a mixed repurposing system for Electric Vehicle (EV) batteries, specifically designed for stationary energy storage applications. This work likely addresses the growing interest in repurposing used EV batteries for secondary applications to extend their lifecycle and contribute to sustainable energy practices. The study may explore the technical aspects of repurposing, efficiency considerations, and the overall feasibility of utilizing retired EV batteries for stationary energy storage. By delving into this innovative approach, the research contributes valuable insights into the potential of mixed repurposing strategies, offering a sustainable solution for energy storage and highlighting the importance of reutilizing EV batteries in the context of circular economy practices.

Gao et al. [6] Make a notable contribution to the field of electric vehicle propulsion systems with their work titled "Optimization of control strategy for dual-motor Coupling propulsion system based on dynamic Programming method." The primary focus of their research is on optimizing control strategies specifically for a dual-motor coupling propulsion system. This innovative approach likely involves employing dynamic programming methods to enhance the efficiency and performance of the dual-motor system in electric vehicles. By addressing the complexities and dynamic interactions within the dual-motor propulsion setup, the study contributes valuable insights into the development of advanced control strategies. The optimization of these strategies is crucial for maximizing the overall efficiency, energy utilization, and performance of electric vehicles, ultimately advancing the state-of-the-art in electric propulsion systems. The research is likely to be of significant interest to the automotive and electric vehicle industries as they seek to improve the efficiency and performance of dual-motor propulsion systems.

Georgious et al. [7] Contribute significantly to the field of energy storage systems with their work titled "Switching Schemes of the bidirectional buck-boost converter for energy storage system." The primary focus of their research is on examining and analyzing the switching schemes employed in bidirectional buck-boost converters, specifically designed for energy storage systems. This study likely delves into the technical aspects of the switching strategies, exploring their impact on the overall efficiency, reliability, and performance of the converters in the context of energy storage applications. By addressing the challenges and intricacies associated with bidirectional buck-boost converters, the research contributes valuable insights into the design and optimization of these systems, ultimately advancing the state-of-the-art in energy storage technology. The findings of this work are likely to have practical implications for the development of more efficient and reliable energy storage solutions, with potential applications in various industries, including renewable energy and electric vehicles.

Herath et al. [8] Make a noteworthy contribution to the field of electric vehicles with their work titled "Design of a dual energy storage power converter for a small electric vehicle." The primary focus of their research is on discussing and elucidating the design aspects of a dual energy storage power converter explicitly tailored for small electric vehicles. This study likely delves into the technical considerations and challenges associated with designing a power converter that accommodates dual energy storage systems, addressing the unique requirements and constraints of small electric vehicles. By focusing on this specific application, the research contributes valuable insights into the development of efficient and compact power converters that are well-suited for the size and energy demands of small electric vehicles. The findings of this work are likely to have practical implications for the design and advancement of power electronics in the context of electric mobility, contributing to the overall development of sustainable and energy-efficient transportation solutions.

Hintz et al. [9] Make a significant contribution to the field of electric vehicles with their work titled "Novel modular multiple-input bidirectional DC–DC power converter (MIPC) for HEV/FCV application." The primary focus of their research is on introducing and detailing a novel modular multiple-input bidirectional DC–DC power converter specifically designed for applications in Hybrid Electric Vehicles (HEVs) and Fuel Cell Vehicles (FCVs). This study likely delves into the technical intricacies and innovations associated with the development of a power converter that can efficiently handle multiple inputs and outputs in the context of HEVs and FCVs. By addressing the challenges unique to these vehicle types, the research contributes valuable insights into the design and optimization of power converters, ultimately advancing the state-of-the-art in electric vehicle technology. The findings of this work are likely to have practical implications for the development of more efficient and versatile power electronics, supporting the continued growth and adoption of environmentally friendly transportation solutions.

Lai [10] Contributes significantly to the field of electric vehicles and DC-microgrids with their work titled "Development of a novel bidirectional DC/DC converter topology with high voltage conversion ratio." The primary focus of their research is on the development of a novel bidirectional DC/DC converter topology that exhibits a high voltage conversion ratio. This innovation is specifically tailored for application in electric vehicles and DC-microgrids. The study likely explores the technical intricacies and design considerations associated with achieving a high voltage conversion ratio, addressing the unique challenges posed by the requirements of electric vehicles and DC-microgrids. By introducing this novel converter topology, the research makes a valuable contribution to the advancement of power electronics in the context of electric mobility and microgrid applications. The findings of this work are expected to have practical implications for improving the efficiency and performance of electric vehicles and DC-microgrid systems, supporting the broader goals of sustainable and resilient energy solutions.

Lai et al. [11] Make a significant contribution to the field of hybrid electric vehicles (HEVs) with their work titled "Development of a bidirectional DC/DC converter with dual-battery energy storage for hybrid electric vehicle system." The primary objective of their research is centered around the development of a bidirectional DC/DC converter specifically designed for hybrid electric vehicle systems. The uniqueness of their approach lies in incorporating dual-battery energy storage, which indicates a more sophisticated energy management system for HEVs. This work likely delves into the technical aspects of designing and implementing a bidirectional converter capable of efficiently managing energy flow between the vehicle's dual batteries, addressing challenges related to power distribution and storage optimization. The outcomes of this research are expected to contribute to advancements in the design and efficiency of energy storage systems in hybrid electric vehicles, ultimately enhancing their overall performance and sustainability.

Lu et al. [12]) Contributes to the field of electric vehicles with their work titled "Energy management of dual energy sources pure electric vehicle based on Fuzzy control." The research focuses on exploring advanced energy management strategies for pure electric vehicles (EVs) equipped with dual energy sources. The dual energy sources could involve different types of energy storage or generation systems. The key innovation lies in the application of Fuzzy control, a computational approach that enables intelligent decision-making based on imprecise or uncertain information. The research likely delves into the development and implementation of a Fuzzy control system tailored for managing the energy flow and utilization of dual energy sources in pure electric vehicles. This work is anticipated to contribute valuable insights into enhancing the efficiency and performance of dual-energy source systems in electric vehicles, thereby promoting the broader adoption of sustainable transportation technologies.

Manjunatha and Manjesh [13] Present their work titled "Design and development of fly-back converter with buck-boost regulator for DC motor used in electric vehicle for the application of renewable energy." The research addresses the design and development aspects of a fly-back converter coupled with a buck-boost regulator, specifically tailored for a DC motor employed in electric vehicles. The emphasis on renewable energy applications suggests a commitment to sustainable energy sources in the context of electric transportation. The study likely delves into the intricacies of the converter and regulator design, with a focus on optimizing performance, energy efficiency, and reliability. By incorporating renewable energy sources into the electric vehicle power system, the research aims to contribute to the advancement of environmentally friendly transportation technologies, aligning with the broader goals of promoting renewable energy integration in the automotive sector.

Mehta and Balamurugan [14] Present their work titled "Buck-Boost converter as power factor correction controller for plug-in electric vehicles and battery charging application." The research focuses on the investigation of a Buck-Boost converter serving as a power factor correction (PFC) controller in the context of plug-in electric vehicles (PEVs) and battery charging applications. Power factor correction is a crucial aspect of electrical systems, ensuring efficient power utilization and reduced harmonic distortions. In the specific context of electric vehicles and battery charging, optimizing power factor can enhance the overall efficiency of the charging process and contribute to the reliable operation of electric vehicles. The study likely delves into the design, simulation, and experimental validation of the proposed Buck-Boost converter as a PFC controller, providing insights into its performance, efficiency gains, and suitability for plug-in electric vehicles and battery charging applications.

Monteiro et al. [15] Contribute to the field with their work titled "Experimental Validation of a novel architecture based on a dual-Stage converter for off-Board Fast battery Chargers of electric vehicles." The research focuses on the experimental validation of an innovative architecture, specifically a dual-stage converter, tailored for off-board fast battery chargers in electric vehicles (EVs). Fast charging is a critical aspect of electric vehicle technology, aiming to reduce charging times and enhance the practicality of EVs for users. The study likely involves the design, implementation, and real-world testing of the proposed dual-stage converter, providing experimental evidence of its effectiveness in the context of off-board fast battery chargers. The findings may contribute valuable insights into the development of efficient charging infrastructure for electric vehicles, addressing the growing demand for fast and reliable charging solutions.

Moradisizkoohi et al. [16] Contribute significantly with their work titled "Experimental Verification of a double-input soft-Switched DC–DC converter for fuel cell electric vehicle with hybrid energy storage system." The study focuses on experimental validation, a critical step in proving the efficacy of the proposed converter design. The specific context is fuel cell electric vehicles (FCEVs), and the innovation lies in the utilization of a double-input soft-switched DC–DC converter. This converter is tailored for FCEVs equipped with hybrid energy storage systems, a key area of interest in enhancing the performance and efficiency of sustainable transportation. The experimental verification likely involves testing the converter in real-world conditions, assessing its ability to efficiently manage power flow between different inputs in the context of a fuel cell-powered vehicle with a hybrid energy storage system. The findings contribute valuable insights to the advancement of power electronics for environmentally friendly transportation solutions.

Moreno et al. [17] Make a significant contribution with their work titled "Energy-management system for a hybrid electric vehicle, using ultracapacitors and neural networks." The study focuses on addressing the crucial aspect of energy management in hybrid electric vehicles (HEVs). The innovation lies in the integration of ultracapacitors and neural networks within the management system, which can play a pivotal role in optimizing the performance and efficiency of the vehicle. Ultracapacitors are known for their rapid charge and discharge capabilities, making them suitable for capturing and releasing energy during dynamic driving conditions. The incorporation of neural networks adds an intelligent layer to the energy management system, allowing it to adapt and optimize based on various driving scenarios and conditions. This holistic approach to energy management is essential for enhancing the overall efficiency and sustainability of hybrid electric vehicles, making Moreno et al.'s work valuable in the field of advanced automotive technology.

Nayak et al. [18] Contribute to the field of electric vehicles with their work titled "Design and simulation of BUCK-BOOST type dual input DC-DC converter for battery charging application in electric vehicle." The study addresses the critical aspect of efficient battery charging in electric vehicles (EVs) by proposing a BUCK-BOOST type dual-input DC-DC converter. The converter design is tailored to enhance the charging process, considering the specific requirements of electric vehicle batteries. The dual-input configuration adds versatility to the charging system, accommodating different power sources and optimizing the charging process for improved efficiency. Through detailed simulation studies, Nayak et al. provide insights into the converter's performance, ensuring its suitability and effectiveness in real-world electric vehicle applications. This work contributes to the ongoing efforts in advancing charging technologies for electric vehicles, a crucial aspect in promoting widespread adoption of sustainable transportation.

Nguyen et al. [19] Make a significant contribution to the realm of electric vehicles with their work titled "Onboard battery Chargers for plug-in electric vehicles with dual functional circuit for low-voltage battery charging and active power Decoupling." In this study, the researchers delve into the critical domain of onboard battery charging systems, specifically designed for plug-in electric vehicles (PEVs). The innovation lies in the incorporation of a dual functional circuit that serves two essential purposes. Firstly, it facilitates low-voltage battery charging, addressing the specific requirements of the vehicle's power storage system. Secondly, the circuit enables active power decoupling, contributing to the optimization of the charging process and overall energy management within the vehicle. This dual functionality enhances the efficiency and adaptability of onboard charging systems, aligning with the evolving needs of plug-in electric vehicles. Nguyen et al.'s work is instrumental in advancing the technology associated with electric vehicle infrastructure and charging solutions.

Omara and Sleptsov [20] Contribute to the field of electric vehicles with their work titled "Bidirectional interleaved DC/DC converter for electric vehicle application." In this study, the researchers introduce a bidirectional interleaved DC/DC converter specifically tailored for electric vehicle applications. The bidirectional nature of the converter implies its capability to efficiently manage power flow in both directions, crucial for the dynamic energy demands of electric vehicles. The interleaved design further enhances the converter's performance by distributing the load across multiple channels, reducing ripple currents, and improving overall system reliability. This innovation aligns with the growing emphasis on enhancing the efficiency and reliability of power electronics in electric vehicles, addressing the unique challenges posed by their energy storage and distribution systems. Omara and Sleptsov's work provides a valuable contribution to the development of advanced power conversion technologies for the electric vehicle sector.

III. DISCUSSION AND FINDINGS

The review of advancements in bidirectional DC/DC converters with dual-battery energy storage for hybrid electric vehicles (HEVs) encompasses a diverse range of studies, each contributing valuable insights and innovations to the field. These converters play a crucial role in managing power flow between different energy storage systems, optimizing energy utilization, and enhancing the overall efficiency of hybrid electric vehicles. The following discussion highlights key findings and trends observed across the reviewed literature:

Dual-Battery Energy Storage Systems: Many studies focus on the integration of dual-battery energy storage systems in HEVs. This approach involves the use of two distinct batteries, each optimized for specific operating conditions. The bidirectional DC/DC converters act as a bridge between these batteries, enabling seamless energy transfer and improving the overall performance of the hybrid system.

Novel Converter Topologies: Several researchers propose novel bidirectional DC/DC converter topologies to address the unique requirements of HEVs. These designs aim to achieve higher voltage conversion ratios, reduced losses, and improved reliability. The development of modular, multiple-input converters and converters with high voltage conversion ratios reflects the ongoing efforts to enhance the efficiency of power electronics in HEVs.

Energy Management Strategies: Energy management is a critical aspect of HEV operation, and various studies focus on optimizing control strategies for dual-battery systems. The use of advanced control methods, such as fuzzy logic and dynamic programming, demonstrates a shift towards intelligent and adaptive energy management systems. These strategies contribute to better utilization of energy from both batteries, maximizing the vehicle's fuel efficiency.

Experimental Validation: Several researchers emphasize experimental validation of their proposed converter architectures. Through rigorous testing and validation procedures, these studies provide practical insights into the real-world performance of bidirectional DC/DC converters. Experimental validations are crucial for ensuring the reliability and effectiveness of these converters in actual HEV applications.

Application in Stationary Energy Storage: Some studies explore the repurposing of electric vehicle batteries for stationary energy storage applications. This approach involves leveraging bidirectional DC/DC converters to adapt EV batteries for use in stationary settings, contributing to the sustainability and lifecycle management of battery systems.

Switching Schemes and Capacitive Components: Certain works delve into the intricacies of switching schemes employed in bidirectional buck-boost converters. Additionally, there is a focus on the modeling and analysis of capacitive components in multiport isolation transformers, highlighting the importance of understanding and optimizing these components for efficient power conditioning in electric vehicles.

In summary, the comprehensive review of advancements in bidirectional DC/DC converters for dual-battery energy storage in HEVs reveals a rich landscape of innovative designs, control strategies, and practical applications. The research community's collective efforts aim to address the unique challenges associated with power management in hybrid electric vehicles, contributing to the ongoing evolution of sustainable transportation technologies.

IV. CONCLUSION

The comprehensive review of advancements in bidirectional DC/DC converters with dual-battery energy storage for hybrid electric vehicles (HEVs) provides valuable insights into the current state of research and development in this crucial field. The synthesized findings from diverse studies reveal a concerted effort to address challenges and optimize the performance of HEVs through innovative converter technologies. The adoption of advanced control strategies, including fuzzy logic and dynamic programming, demonstrates a commitment to optimizing energy management in dual-battery HEV systems. These strategies not only enhance overall vehicle efficiency but also contribute to the seamless integration and utilization of energy from different storage sources. A notable trend in the reviewed literature is the emphasis on experimental validation. Many studies recognize the importance of validating proposed converter architectures through practical testing. This commitment to real-world validation enhances the credibility and applicability of the research findings, ensuring that proposed solutions are viable for deployment in actual HEV scenarios. Some studies extend the scope of their investigations beyond vehicular applications, exploring the repurposing of electric vehicle batteries for stationary energy storage. This expansion of focus aligns with broader sustainability goals, acknowledging the potential for leveraging dual-battery systems in diverse energy storage contexts. The in-depth exploration of switching schemes in bidirectional buck-boost converters and the analysis of capacitive components in multiport isolation transformers demonstrate a nuanced understanding of the underlying electrical components.

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